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Economic evaluation of common reed potential for energy production: A case study in Wuliangsuhai Lake (Inner Mongolia, China)

Jan Felix Köbbing [a,*], Francesco Patuzzi [b], Marco Baratieri [b], Volker Beckmann [a], Niels Thevs [a], Stefan Zerbe [b]

[a] Institute of Botany and Landscape Ecology, University of Greifswald, Soldmannstraße 15, 17487 Greifswald, Mecklenburg-Vorpommern, Germany
[b] Faculty of Science and Technology, Free University of Bozen-Bolzano, Piazza Università 5, 39100 Bolzano, Italy

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ABSTRACT

Wuliangsuhai Lake is one of the largest wetlands in Inner Mongolia, China, half covered by large and highly productive Common Reed (*Phragmites australis*) stands. However, benefits from current utilization practices do not cover the costs of harvesting. Against this background, Wuliangsuhai Lake is taken as a case study for the assessment of the potential use of reed biomass for energy production. Taking into account, both the present and the potential reed availability, four scenarios are considered, i.e. (1) a decentralized application in household stoves, (2) a centralized reed supplied combined heat and power gasification, (3) a direct combustion plant and (4) a co-firing in existing coal plants. Two field campaigns have been conducted firstly collect information about the current situation of the reed and coal market and secondly to measure reed above-ground biomass. The suitability of reed for thermochemical conversion processes has been evaluated by means of chemical-physical, calorimetric, and thermal analyses of the samples. The potential energy production is valued regarding the profitability on the current Chinese energy market. Possible subsidies for reed as a renewable resource are taken into account. The evaluation has shown that reed has the potential to act as an energy feedstock. In relation to the considered study site, reed energy use can be profitable on the household level, in CHP combustion plants and in co-combustion. Gasification CHP plants are not economic feasible under current conditions. The results show that reed can be a sustainable alternative to highly health and environment damaging coal.

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1. Introduction

Presently, China is one of the countries with the most dynamic economies in the world. The energy necessary to supply this fast economic growth is mostly produced from coal (74% in 2011, Table 1), which is cheap and easily available. The drawbacks are the high emission of greenhouse gases and problems connected to air pollution. Producing “clean” energy

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* *Corresponding author*. Tel.: +49 (0)3834 864137; fax: +49 (0)3834 864114.
E-mail addresses: jan.koebbing@stud.uni-greifswald.de, jankoebbing@web.de (J.F. Köbbing).
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Table 1 – China's energy balance in millions of tonnes of oil equivalent [Mto] on a net calorific value basis for 2011 [1].

	Production	Imports	Exports
Coal and peat	1823.4	98.8	18.2
Crude and oil products	203.0	308.8	33.4
Natural gas	85.9	24.5	2.9
Nuclear	22.5	0.0	0.0
Geothermal, solar, hydro, etc.	101.2	0.0	0.0
Biofuel and waste	218.4	0.0	0.0
Electricity	0.0	0.6	1.9
Total	2432.5	432.8	54.0

is one of the most challenging tasks for China in the 21st century [1].

China is planning to tackle this challenges by increasing the share of renewable energies from 8% in 2013 to 15% in 2020 [2]. Whereas wind, photovoltaic, and hydropower have been mostly used for electricity production, biomass is often burned in rural areas for heating and cooking [2,3]. The role of the biofuels and waste, however, is relatively small, representing only 8.9% of the total energy production in 2011 (Table 1). Co-firing of biomass in conventional coal plants due to missing financial subsidies took only place in pilot cases, e.g. in the Shiliquan power plant [4]. Up to now, heat production from biomass relies mostly on small-scale technology, e.g. stoves for local heat production by combustion or digestion. Nonetheless, biomass resources (agricultural residues, grassland biomass and forest residues) can play a significant role on substituting coal, being potentially equal, in terms of stored energy, to almost 30% of China energy consumptions [5]. According to China's 12th Five-Year Plan for Renewable Energy, the production of biogas in rural areas is intended to increase to 50 million households by 2015 [2]. 7 billion tonnes of solid waste are produced annually, with a proportion of 60% biomass waste [6]. According to [7], the potentially available amount of crop residues in China in 2009 was 806.9 million tonnes, with a net available amount of about 505.5 million tonnes per year, accounting for more than 8% of the total energy consumption of the country. In order to ensure soil fertility, a considerable part of the biomass should be reserved and re-used as soil improvement on the fields. Reed is mostly overseen in the potential biomass available in China, due to the fact that it is not a crop residue and therefore cannot be calculated from official crop yields [8,9]. From literature sources concerning the paper market, the potential of reed biomass is estimated to 2.6–2.7 million tonnes in 2004 and forecasted in 1998 to be 4.2 million tonne in 2010 [10]. According to [11], 95% of the collected reed has been used for paper production in 2004, being the main competing sector for the energetic use of reed biomass. Nonetheless, in order to control pollution through the restructuring of pulp industry from small-scale mills to massive mills reliant on wood-based pulp and recycled paper [12], many traditional non-wood paper mills have been closed down in China recently, opening new scenarios for the utilization of reed for energy purposes. Other traditional reed utilizations, such as fodder and mat waving, are of only marginal importance.

Whereas urban centres rely mostly on central heating system and power plants fed with non-renewable energy sources like coal and oil, remote rural areas, mainly in Northern and Western China, still rely on decentralised heating systems. Simple low efficiency open coal stoves are used for heating and cooking, often leading to indoor air pollution and resulting health problems [3,13]. However, use of agricultural waste and residues is also responsible for job creation in rural areas, e.g. in harvesting, transportation, processing, and trading of biomass [8,13]. Experiences in Ref. [14] have shown that such kind of traditional stoves can be improved to increase their effectiveness on reducing indoor pollution.

Renewable energies in China cannot compete with fossil energies and therefore need governmental support. China's “Renewable Energy Promotion Law” (2006) includes institutional reforms, setting off emission reduction targets and a bundle of financial subsidies, among others the construction of household biogas digesters, guarantee for a connection to the grid, competitive tendering for renewable energy and a feed-in tariff for electricity from renewable energies [8,15–17]. Co-combustion of biomass in coal plants is not supported under the feed-in tariff up to now, as it requires a biomass share of a minimum of 80% [4,18]. In the program of promoting renewable energies, a special focus on rural and remote areas is included. In these areas, local energy like biomass, wind or solar power might be an option to satisfy the energy demand [13]. Therefore, in 2020, 30 million kilowatts electricity shall be generated by solid biomass [19]. With regard to biomass energy feedstock, straw and cotton stands are the most dominant plants. It is applicable for power plants as well as on the household level.

Inner Mongolia's climate conditions and geographical location make it in particular suitable for the generation of electricity from wind and sun [20], but also biogas generation becomes more and more popular, due to huge amounts of manure available from livestock farming [21]. Due to the very low mean winter temperatures, the biogas use in normal plants is limited to a maximum of 9 months per year [21]. Focusing on reed as an energy sources, it plays only a very minor role in China due to the described constraints, usually only used to enliven fire. Therefore no data are available about the profitability of reed as energy feedstock yet.

One of the first scientific studies on reed utilization for energy purposes date back to the 1980s in Sweden, in particular for the application of reed in direct combustion [22]. Nevertheless, in the following years, even if this species has been widely studied for its phytodepuration potential [23–27], few experiences can be found in the international literature concerning the energy utilization of *Phragmites australis*. In fact, the low bulk density (20–60 kg m^{-3}) of untreated reed makes it unattractive for long distant transportation (more than 10–30 km) and increases handling and storage costs. Only in recent years, reed biomass as energy source again increasingly attracted attention by researchers and practitioners, mainly in Europe [28]. Most investigations deal with the combustion of reed [28–33], some with biogas production [31,34]. Besides this, a promising but not yet completely studied application of common reeds seems its thermochemical conversion through pyrolysis [35–37] or gasification

[38–40], in the perspective of converting the biomass into liquid or gaseous fuels that can be used in a more efficient way compared to the direct combustion of a solid fuel. Why former work mostly focussed on the heating value of reed, the present study is the first economic-energetic reed evaluation worldwide.

For combustion, dry reed (15–20% moisture content) is required, which requires a late winter-harvest [41]. During the cold winter months in Inner Mongolia, when the thickness of the ice is sufficient, frozen reed can be cut above water level with conventional agricultural tractors. Without such an ice layer a more costly harvest with site adapted technique is necessary.

In addition, according to [42], winter harvested reed is a better fuel from the point of view of ash composition and quantity. As other herbaceous biomasses, reed is characterized by an ash content higher than that of woody biomass, with high concentrations of elements such as alkalis and silica that, along with the chlorine content of the fuel, tend to form highly volatile and/or easily melted compounds that can cause operational problems such as slagging (deposition on sections mainly exposed to radiant heat of molten or half molten ash particles that stick to the hot furnace walls and slowly accumulate), fouling (condensation of inorganic vapours on the relatively cooler surfaces of convective pass) and corrosion [43]. With regard to winter-harvested reed, the amount of alkali metals is higher in summer-harvested reed and this negatively affects the ash fusibility, decreasing the ash melting temperature and the formation of ash deposits [42]. Transportation distance and mostly also combustion equipment (e.g. stoves) require a chopping and compaction of the reed into bales, pellets or briquettes. This lowers the global energy balance and causes additional costs.

Biogas utilization of reed requires “green” spring or summer reed, which is wet and has a high nutrient content and a suitable carbon to nitrogen (C/N) ratio. By anaerobic digestion, 1 kg of chopped reed produces 0.4–0.5 m^3 of biogas with a maximum methane content of 55–60% [31]. Often, reed is mixed with other agricultural waste. Up to now biogas production from reed worldwide only takes place on a small scale due to difficulties in harvesting the reed in summer and potential conflicts with nature conservation, e.g. breeding birds in the reed bed in spring. The biofuel (bio-ethanol) production from reed has been mainly conducted at the experimental scale [44–47]. However, recent developments demonstrated the applicability at the commercial-scale of second generation bioethanol from non-food biomass (e.g., a plant of 75 million liters a year has been recently built in northern Italy [48]).

The aim of this paper is to present the results of a techno-economic evaluation of reed potential as energy source, with particular reference to Wuliangsuhai wetland region (Inner Mongolia, China). It seeks to answer the following research question: Can reed be a technically feasible and economically competitive energy feedstock under the current bio-physical and market conditions at Wuliangsuhau Lake? The lake collects the drainage water of the Hetao irrigation system, which leads to a high degree of eutrophication and a consequent reed coverage of half of its area. In order to clean the water and ensure the lake accessibility, a regular reed harvesting is needed. Currently, the harvesting of reed for the pulp and paper industry is hardly profitable. The high transport costs to paper mills far away from the lake reduces its economic profitability [49]. The utilization of reed for energy purposes may be a possible application to improve the local livelihood in terms of income and heath. From the perspective of technology, this work focuses on thermochemical conversion (combustion, pyrolysis and gasification) of reed and also against the background that the use of biogas in Inner Mongolia is limited by a very low winter temperature and that the biofuel production from reed is still in an experimental stage.

2. Materials and methods

2.1. Site description

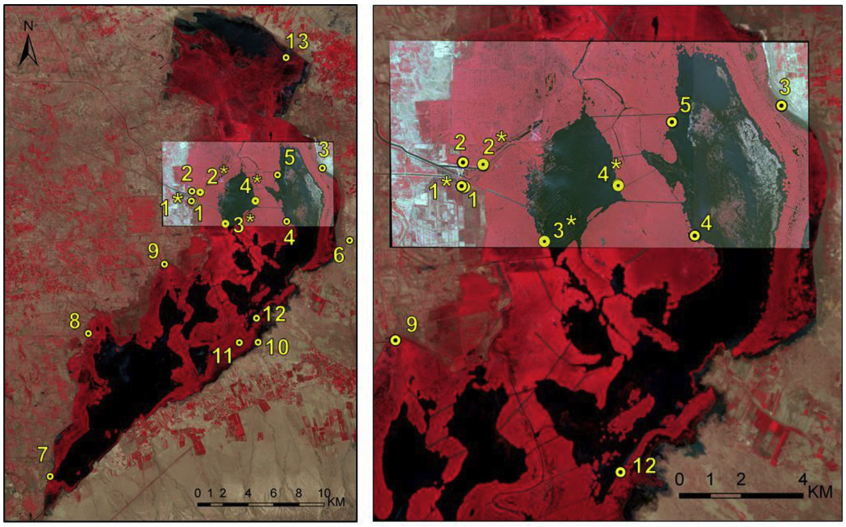
Wuliangsuhai Lake (40°47′–41°03′N, 108°43′–108°57′E) is located in the Bayannaoer Prefecture of Inner Mongolia Autonomous Region (China), at the eastern end of the Hetao irrigation system. The largest city in the area, with a population of about 180,000 people, is Linhe, the capital of Bayannaoer, Hanghou and Wuyuan, the two other towns in the catchment, and Urad Qianqi (named also Wuliateqianqi), the town just down-stream of the lake, have a population of about 60,000 people [50].

With an area of almost 300 km^2, Wuliangsuhai is the largest wetland complex in the Yellow River Basin. The water volume is about 250–300 million m^3 and the water depth ranges from 0.5 to 3 m. In about 80% of the lake, it is between 0.8 and 1 m [51]. The mean depth is 70 cm [52]. According to the survey performed during a 3-years restoration project by the Inner Mongolia Environmental Science Institute (IMESI), the Norwegian Institute for Water Research (NIVA), and the Swedish Environmental Research Institute (IVL) in the first half of the 20th century, the lake has been much larger (almost three times) and considerably deeper than today [53].

The main recharge of the lake originates from drainage waters from the Hetao Irrigation District, municipal sewage and industrial wastewater [51]. As a result, Wuliangsuhai Lake has been increasingly subjected to eutrophication and almost half of the lake wetland is currently covered by emergent vegetation, mainly *P. australis* and some scattered stands of *Typha latifolia*. The open-water area is covered by submerged vegetation, mainly *Potamogeton pectinatus* [54]. The reed area increased from 17 km^2 in 1975 to 188 km^2 in 2010 [49,55].

2.2. Above-ground biomass quantification of reed

In October 2011, reed samples have been collected, in the Wuliangsuhai wetland area, both for the non-submerged (on land) and for the submerged (inside the lake) reed stands. The average above-ground biomass has been determined following the approach used by Refs. [56], on the basis of the stem density and the average total plant weight of the 5 sampled plants. In addition, for each harvested plant, the stem length and the basal stem diameter have been measured and the number of leaves has been counted. Inside a Quickbird satellite image (8th of July 2011) edge, 5 sampling plots have been selected, 3 non-submerged and 2 submerged reed



(a)

(b)

Fig. 1 – Sampling points in the Wuliangsuhai Lake and adjacent wetlands with (a) covering the whole wetland (background: Landsat) and (b) inside the Quickbird scene. Most of the samples have been collected in October 2011, asterisked points refer to samples collected in September 2012.

stands (Fig. 1). Each plot has been placed randomly and 4 subplots (squares with side length 0.5 m) have been fixed, keeping the same distance from a central fixed point. On each subplot, the stems were counted, and the 5 stems closest to the diagonal were cut.

A Student's *T*-test for two populations has been carried out to assess the differences in length, basal stem diameter, and above-ground biomass between the non-submerged and submerged reed stands.

2.3. *Reed qualitative characterization*

Several samples have been collected also in other points of Wuliangsuhai wetland area (Fig. 1a) and subsamples from stems have been characterized by means of elemental and calorimetric analysis. The choice to focus the analyses only on stems is due to the weight distribution in *P. australis*, that – according to [57] – is more or less 47% in roots, 37% in stems, 15% in leaves and 1% in inflorescences. The samples were only aboveground collected, therefore these percentages became 70%, 28% and 2% for stems, leaves and inflorescences, respectively.

The moisture content of the collected samples has been determined according to the UNI CEN/TS 14774–2. Stem subsamples have been dried at 45 °C for 48 h and ground with a Retsch Mill MM400. Ash content (UNI EN 14775), elemental composition (UNI EN 15104), sulphur and chlorine content (UNI EN 15289), phosphorus (UNI EN 15290) and Lower Heating Value (UNI EN 14918) have been determined. Due to the high ash content, a more detailed analysis of the ash melting behaviour has been performed on three selected stem samples (one collected on non-submerged, one on submerged stands and one in a storage area, where reed harvested in previous years are deposited), according to UNI CEN/TS 15370–1. Reeds can withstand extreme environmental conditions, including the presence of toxic contaminants such as heavy metals [24–27]. There are many cases in which, as other wetland plants, reed is utilized for the removal of pollutants, including metals [58,59]. For this reason, the metals' content of the three selected samples has been determined according to the UNI EN 15297.

In addition, the thermal behaviour of reeds have been characterized using a simultaneous thermogravimetric analyser (STA 449F3, Netzsch). This technique combines both, the heat flux differential scanning calorimetry (DSC) and thermogravimetry (TG). STA analyses have been performed at a constant heating rate of 20 °C/min under inert nitrogen atmosphere in a temperature range from 30 to 1000 °C.

2.4. *Interviews*

In order to collect information about the current situation of the reed market, several open interviews have been carried out in October and November 2011 and September 2012 in Linhe, Wuliangsuhai Lake, Baotou, and Hohhot (Inner Mongolia). Before the fieldwork started, a stakeholder analysis has been performed and seven groups with several subgroups have been identified which are the lake administration, scientists, energy companies, reed harvester, and processor, final users of reed, fishermen and stakeholder involved in tourism. In total, 56 interviews have been conducted. Local project partners have introduced officials, scientists have been contacted after a literature review of past and on-going researches in the lake, and local interviews have been randomly selected by asking people on the street. At Wuliangsuhai Lake, the villages along the lakeshores and the reed storing grounds (points number 6 and 10 in Fig. 1) have been visited.

The interviews, according to [60], have been based on a qualitative questionnaire with formal (closed) questions (e.g.,

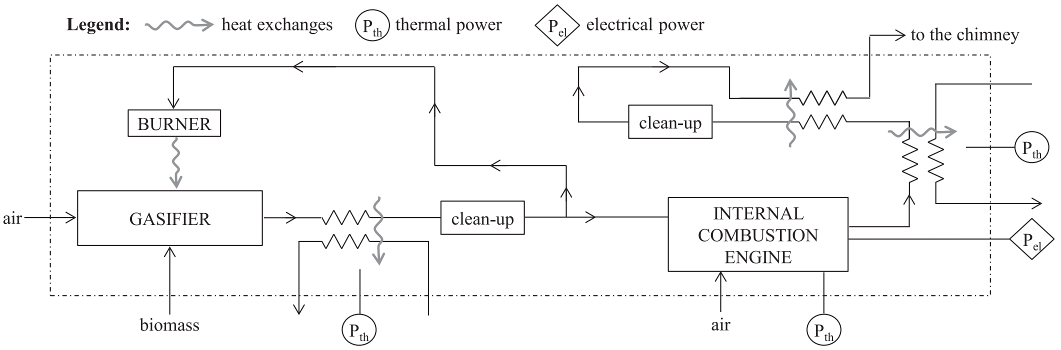


Fig. 2 – Schematic representation of the considered CHP power plant layout, adapted from Ref. [71].

identity, name) and a topic list for semi-structured (open) inquiries. The core issues of the qualitative investigations have been addressed in a conversation-like manner by means of (mostly) open-ended questions. This design has been chosen in order to maximize – during the relatively short fieldwork time – the required information, considering also the difficulty on obtaining detailed and reliable information only through literature and web research.

Although the data collection technique has been mainly based on interviews, the obtained data has been triangulated. Triangulation means to combine different data sources, like interviews and literature sources, to check the reliability and correct integrity [61].

2.5. *Energy potential assessment of reed*

According to the measured above-ground reed biomass and its average lower heating value, the potential of reed as energy source has been evaluated considering four different scenarios, i.e. (Scenario 1) the production of heat through direct combustion in straw furnaces (distributed heat generation), (Scenario 2) the centralized combined heat and power (CHP) generation in a dedicated gasification plan, or (Scenario 3) in a direct combustion facility (grate furnace systems coupled with a conventional steam turbine). In addition, the possibility of co-firing reed in an existing coal-heating plant has been considered (Scenario 4).

Up to now in the rural areas of China, household energy is mainly produced by means of direct coal or biomass combustion [62,63] with methods characterized by very low energy efficiencies (e.g., 10–15% for the traditional stoves burning crop residues [64] and 7–10% for the Kang, a kind of heating beds in rural northern China [65,66]). This causes serious indoor air pollution related to respiratory aerosols, SO_2 (in particular when coal is burned), and CO emission [67].

Scenario 1 represents a possible solution to mitigate this problem, assuming that houses in the Wuliangsuhai area are provided with high efficiency biomass stoves to replace the low efficiency and polluting coal-fired stoves, as done in some villages of Hubei province in the frame of CDM (Climate Development Measurements) projects financed by the United Nations Framework Convention on Climate Change [68]. According to the presented projects, thermal efficiencies ranging from 79.8% to 87.0% can be reached using specific stoves on which the biomass is firstly partially oxidized and then the producer gas is burned with secondary air [69]. These efficiency values seems quite optimistic, so the average value has been reduced by a 10% factor in order to take into account realistic effects such as inhomogeneity of the feedstock, non-optimal moisture content and non-nominal operating conditions.

The improvement of the stove efficiency would lead to a more efficient combustion, reducing the pollutants emissions with a beneficial impact on the indoor air quality and consequently on the health of the inhabitants. In fact, it is reliable to assume that well-designed, carefully installed, and routinely maintained improved stoves could result in a 75% reduction in exposures [70]. Anyway, focusing on indoor emissions, this scenario would not completely solve the problem, although mitigating it. Therefore, even if the improvement of the distributed generation through the adoption of biomass stoves would be the scenario with the lower investment costs, it can be argued that the ultimate solution should be reducing indoor direct combustion, rather than reforming it [66]. In this perspective, the Scenario 2 considers a centralized CHP plant based on reed gasification, suiting a previously developed multistage model of a CHP biomass plant [71]. The power plant layout (Fig. 2) consists of a first section where the producer gas is produced and a second section where the producer gas is exploited to generate electrical and thermal power. The producer gas production section has been modelled as an air gasifier operating in ideal conditions, which can simulate the pyrolysis and air gasification process. The chemical reaction can be endothermic or exothermic depending on the process conditions. In the first case, the heat is provided by a burner that is fed through a producer gas spilling, while for exothermic operation the heat is supposed to be discharged. Before feeding the CHP plant, producer gas is piped through heat-recovery and clean-up sections.

According to the results of elemental and calorimetric analyses, the average reed composition and energy content have been calculated and used as input for the model, in order to estimate the thermal and electrical conversion efficiency. The first stage of the model is the gasification unit, simulated through an enhanced gas–solid equilibrium approach, previously tested versus experimental available data and based on the minimization of the Gibbs free energy [72]. This allowed the estimation of the theoretical yield and equilibrium

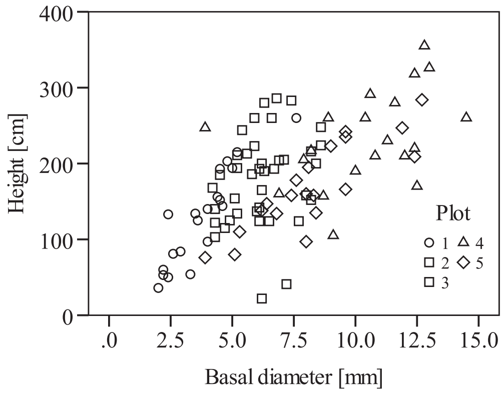


Fig. 3 – Scatterplot of height versus basal diameter of the sampled reed (*P. australis*).

composition of the reaction products (producer gas and char) of reed thermochemical conversion processes (pyrolysis and gasification). The model consists of a code written in Matlab environment that handle chemical reaction equilibria, implementing the Cantera software library, a collection of object-oriented software tools for problems involving chemical kinetics, thermodynamics and transport phenomena [73].

An alternative option for the combined heat and power production that has been considered in Scenario 3 is the direct combustion in a grate furnace system coupled with a conventional steam turbine. Because of the low ash melting temperature of reed, a vibrating grate is supposed to be installed. The advantage of such kind of system, compared to fixed grate, is that the constant vibration does not allow the formation of large molten ash agglomerates, even if it leads to an higher amount of ash particles in the flue gas that could require more extensive measures for flue gas cleaning [43]. In Denmark, many similar plants have been erected over the last 25 years using wheat straw as a fuel [74]. For the scenario evaluation, thermal and electrical efficiencies of 62.8% and 24.4% respectively have been assumed (average efficiencies of existing plants in Denmark).

Finally, for the evaluation of the co-combustion of reed in the existing coal heating plants in Urad Qianqi, a town in the south of Wuliangsuhai area, a sharing of 20% in weight of reed has been assumed. With a sharing lower than 5% a grinding pre-treatment would not be required. Nonetheless, it would correspond to an amount of reed not interesting for the present case study. Under the considered scenario, in order to ensure a stable combustion, reed should be well shredded before the mixing with pulverized coal in the furnace. In addition, the pre-treatment would reduce the risks of malfunction of the fuel-handling systems, avoiding an increase in running costs [75].

3. Results and discussion

3.1. *Above-ground biomass*

A preliminary check of the collected data has been performed plotting the measured heights versus the basal diameters for all the field observations (Fig. 3). As expected, the height shows a positive trend respect to the basal diameter. The statistics of height and basal diameter distributions are presented in Table 2. For both the parameters, performing a Student's *t* test for two populations, the values are significantly higher in the submerged than on the non-submerged reed stands ($P < 0.05$).

The distribution of the above-ground biomass along the different plots is shown in Fig. 4a. Considering all the observations, the average above-ground biomass is 14.1 t/ha with a standard deviation of 7.1 t/ha. This value is in perfect agreement with the dry matter yield of *P. australis* reported by Refs. [76,77]. The average above-ground biomass is 11.4 and 18.2 t/ha for the non-submerged and for the submerged reed, respectively. The distributions in the non-submerged and in the submerged reed stands seem equally concentrated (standard deviation of 6.1 t/ha and 6.8 t/ha respectively). Performing a Student's *t* test for two populations, the average above-ground values are significantly higher by comparing submerged and terrestrial stands ($P < 0.05$).

The above-ground biomass has been measured with the same approach also in September 2012 (Fig. 4b). In that case, the results have been slightly lower, i.e. 6.9 t/ha in the non-submerged and 18.1 t/ha in the submerged reed stands, with, a respectively, a standard deviation of 3.3 t/ha and 8.1 t/ha respectively. The average value of all the observations (both years) is 13.4 t/ha with a standard deviation of 7.5 t/ha.

3.2. *Feedstock characterisation*

The moisture and ash content, the lower heating value, and the elemental composition of *P. australis* samples are shown in Table 3. In addition, the metal contents and the ash characteristic temperatures of three selected samples (one collected in non-submerged, one in submerged stands and one in a storage area) are given in Table 4.

Moisture content is one of the main parameters that have to be considered in the assessment of a feedstock as far as it concerns its applicability in thermochemical conversion processes. The collected reed samples, and in particular the ones collected in the water, are characterised by a high moisture content. Thus, a first phase of on-site air-drying have to be considered before processing the biomass. Some samples contain a high content of chlorine and sulphur (Table 3). This could cause problems regarding emission and corrosion, thus

Table 2 – Average values and standard deviations (±) of height and basal diameter according to the collected reed samples.

Parameter	Non–submerged reed ($n = 60$)	Submerged reed ($n = 40$)	Average ($n = 100$)
Height [cm]	161.9 ± 65.5	201.9 ± 68.0	177.6 ± 68.9
Basal diameter [mm]	5.4 ± 1.7	9.3 ± 2.6	7.0 ± 2.9

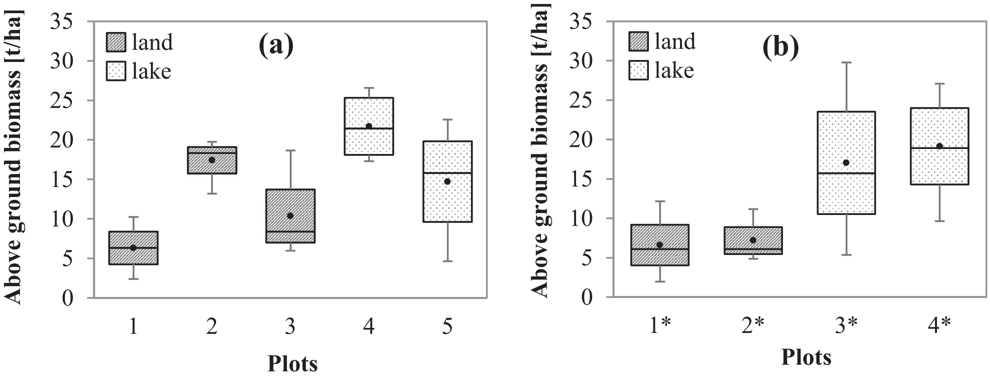


Fig. 4 – Boxplots of the above-ground distribution in the different plots, according to the sampling campaign performed in (a) October 2011 and (b) September 2012.

it should be taken in consideration during the process design and impact assessment. Another aspect to take into account is the high ash content that can represent a problem in the management of the system, in particular if the melting temperature of the ash is low (formation of slag).

Results suggest that reeds seem a suitable feedstock in medium temperature processes which means lower than 800–900 °C. Reeds are able to accumulate pollutants due to their phytodepuration potential [23]. Thus, it is important to consider their heavy metals' content (Table 4). In fact, after thermochemical conversion processes most of the metals will be concentrated in the ashes. As far as the thermal behaviour of reed is concerned, thermogravimetric analysis on some of the collected samples (data not shown) confirmed the behaviour results in previous studies [78], characterized by two main reactions (the first at around 280–300 °C and the second at around 350–380 °C) which are also due to the main weight loss during thermal degradation.

3.3. *Energy market in the Wuliangsuhai area*

In order to investigate the possible application of reed for energy production, some interviews about the local electricity and heating system have been conducted. The energy supply highly depends on coal, which is cheap and locally available. Two different heating systems can be distinguished in the area. The town Urad Qianqi is heated through a district heating system supplied by three coal-heating plants, which can heat 3.5 km^2 in the whole district, reaching consumers to a distance up to 3 km from the town. As a consequence, people living in rural areas, including Wuliangsuhai Lake area, are not connected to that heating system. Most of the households use simple coal stoves for heating.

According to the data collected during the survey at the coal plant and the interviews to grid company employees, the price at which the company that manage the heating plant purchase the coal increased from 340 to 410 CNY/t in 2010/11 to 480 CNY/t in 2011/12 (10 CNY corresponded approximately to 1.2 € or 1.6 $ in 2011). The heat is sold by the heating plant company to the grid company for 0.2879 CNY/kWh and bought by the households for 0.5–0.6 CNY/kWh. The grid company, which manage the district heating and provide heat to a total floor area of 3.5 km^2, obtain a contribution margin of 22 CNY/m^2 per year (equal to 3.7 CNY/m^2 per month, being the heat provided 6 months a year). The specific coal consumption is 35–45 kg/m^2 per year. An equivalent coal selling price can be then calculated dividing the price at which the company sell the heat by the coal consumption for producing it, resulting equal to 490–630 CNY/t.

For rural areas, the situation is quite different. The coal is sold in village coal shops which buy it, depending on the market price, for 600–680 CNY/t and sell it for 700–780 CNY/t.

Table 3 – Chemical and physical characterization of *P. australis* stem tissues.

IDs	unit	2	3	4	5	6(S)	7	7(S)	8	9	10	11	12	13
Moisture	$\%wt_{ar}$	16.0	32.2	62.4	47.0	12.2	30.9	12.8	12.7	20.9	27.5	24.0	51.7	20.0
Ash	$\%wt_{dry}$	3.8	4.2	3.3	4.4	4.3	4.5	2.7	7.1	7.0	7.8	3.3	6.8	5.2
LHV	MJ/kg_{dry}	17.25	16.90	17.52	16.85	17.17	17.43	17.82	16.76	16.96	16.73	17.38	16.44	17.03
C	$\%wt_{daf}$	49.3	49.3	48.8	47.8	49.1	49.4	49.0	49.0	48.7	48.7	49.2	49.2	49.3
H	$\%wt_{daf}$	6.4	6.5	6.4	6.4	6.5	6.4	6.4	6.5	6.2	6.4	6.6	6.7	6.4
N	$\%wt_{daf}$	0.3	0.4	0.3	0.3	0.5	0.5	0.3	0.3	0.3	0.4	0.2	0.4	0.5
O	$\%wt_{daf}$	43.0	42.5	43.4	44.5	42.9	43.0	44.0	43.4	43.9	43.3	43.4	42.4	42.6
S	$\%wt_{daf}$	0.1	0.1	0.2	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1
Cl	$\%wt_{daf}$	0.9	1.2	0.9	0.7	0.8	0.6	0.2	0.7	0.8	1.1	0.5	1.1	1.1
P	mg/kg_{dry}	119	287	61	103	116	176	82	181	86	126	71	240	175

(S) = storage, daf: dry ash free.

Table 4 – Metals' content and ash melting behaviour of *P. australis* stem tissues.

IDs	3	4	6(S)
Metals [mg/kg]$_{dry}$			
As	0.8	0.4	0.7
Cd	0.2	0.1	<0.1
Cr	5.0	1.2	3.3
Cu	1.0	0.7	0.6
Hg	<0.1	<0.1	<0.1
Mn	62.5	71.2	104.4
Ni	1.5	1.3	1.1
Pb	0.7	1.0	0.5
Ash characteristic temperatures [°C]			
Deformation	842	839	871
Hemispherical	1047	954	978
Flowing	1115	1092	1094

According to the collected information, the coal consumption for heating a small flat for 3–4 people is between 2 and 3 t/year. Assuming a typical flat extension of 60 m^2, this corresponds to 33–50 kg/m^2 per year. An additional tonne of coal is needed if coal is used also for cooking.

3.4. *Reed market in the Wuliangsuhai area*

In the Wuliangsuhai Lake area, annually around 100,000 tonnes of reed biomass are harvested in winter (see Fig. 5) originating from a total reed cover of 188 km^2, corresponding to half of the lake area. This reed is harvested in winter by employed local farmers, stored along the shore, pressed into bales and finally transported to two paper mills in Ningxia province, 700 km far away [79]. The long transportation distance lowers the net benefits of reed harvesting for the local people significantly. On the long run, utilization possibilities with higher net benefits have to be found.

For the harvested reed raw material originating from the inside of the Wuliangsuhai Lake, a price of 370 CNY/t can be achieved (moisture content app. 18%) [49]. Currently the reed is pressed into bales for the long-distance transportation.

3.5. *Evaluation of reed potential as energy source*

3.5.1. *Equilibrium model and CHP efficiencies estimation*

Starting from the composition and the lower heating value of the samples collected both in non-submerged and submerged reed stands, the average composition and the lower heating value have been calculated (Table 5), assuming a moisture content of 10%, a typical value that can be reached after an air-drying pre-treatment. The average elemental composition and calorific value have been used as input of the thermodynamic equilibrium model.

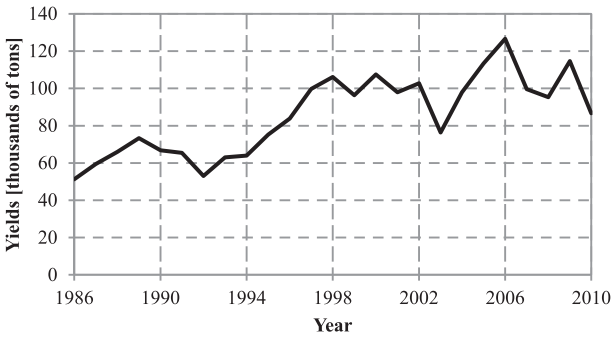


Fig. 5 – Harvested reed in Wuliangsuhai Lake 1986–2010 [80].

Table 5 – Average composition of reeds (as received basis), used as input of the thermodynamic equilibrium model.

Moisture	Ash	C	H	N	O	S	LHV
[%wt$_{ar}$]							[MJ/kg$_{ar}$]
10.0	4.7	39.6	5.2	0.3	40.1	0.1	15.07

Fig. 6 shows the producer gas molar composition for reed pyrolysed at different temperatures and a process pressure of 1 bar. According to [72], methane and carbon dioxide formation are favoured at lower temperatures, and at higher temperatures carbon monoxide and hydrogen are the dominant equilibrium products. This is mainly due to the increasing importance of the endothermic water gas reaction that causes a corresponding decrease of the producer gas steam content (generated by the drying of the feedstock). Furthermore, carbon dioxide trend goes through a maximum according to its exothermic formation and endothermic conversion.

The equilibrium composition versus the equivalence ratio (ER, ratio between the oxygen fed to the gasifier and the stoichiometric quantity of oxygen needed for the complete oxidation of the species) has also been evaluated (Fig. 7). The increase of the ER parameter causes a proportional increase of the N_2 molar fraction due to the greater amount of air fed to the reactor [72].

The producer gas heating value represents the useful energy output from the gasification process. An increase of the amount of gasifying agent tends to lower the producer gas LHV, mainly decreasing its CH_4 and H_2 molar concentrations. The global enthalpy variation along the conversion process has been computed taking into account all the enthalpy fluxes i.e. enthalpies of the biomass, reaction products and gasifying agents. This quantity, if positive (or negative), represents the

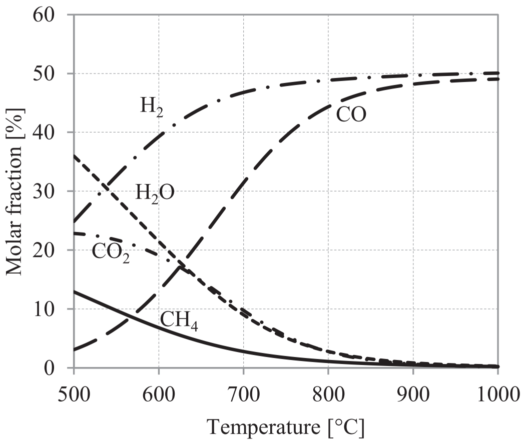
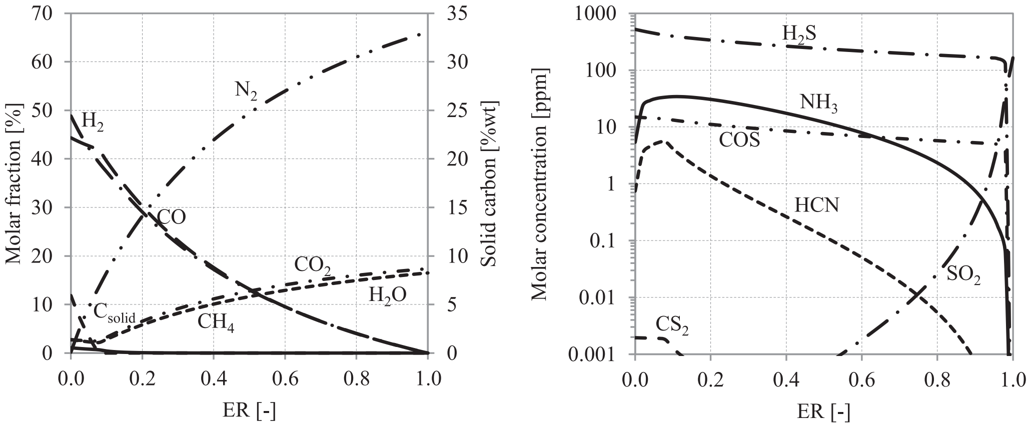


Fig. 6 – Producer gas equilibrium composition versus process temperature under pyrolysis conditions and pressure of 1 bar.



(a) (b)

Fig. 7 – Producer gas equilibrium composition and solid carbon versus equivalence ratio under partial oxidation and steam gasification of reed at 800 °C and 1 bar, (a) major and (b) minor components.

amount of energy that has to be supplied to (or is released by) the process itself. The net process enthalpy variation is an increasing function of the process temperature. In addition, a rising of ER determine an increasing of the partial oxidation process exothermicity [72].

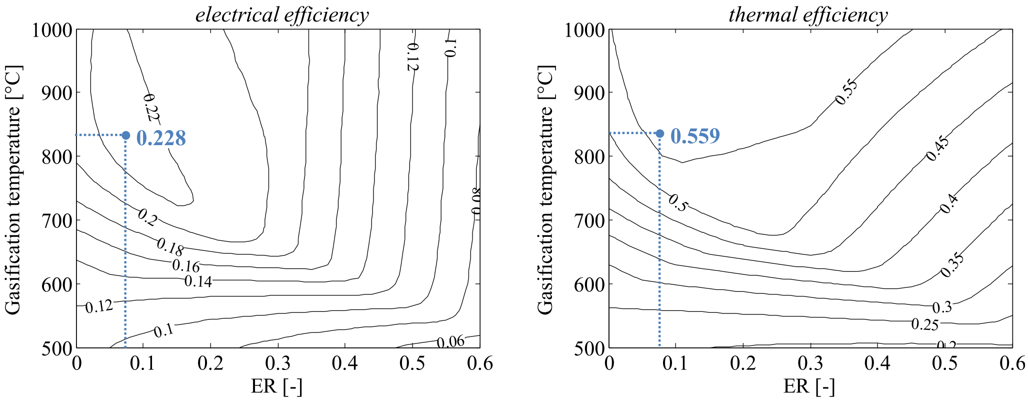
The efficiency of the whole CHP system has been evaluated supplementing the simulation of the gasification stage with the energy balance of the cogeneration set (i.e., internal combustion engine). The electrical efficiency is maximized when the gasifier is operated at 870 °C and ER = 0.06. Under these conditions, the thermal and electrical gross efficiency results equal to 55.9% and 22.8%, respectively (Fig. 8). These values have been used in the scenarios evaluation.

3.5.2. *Scenarios evaluation*

The survey results clearly show the fast growing energy demand in Urad Qianqi. The living space in the city increased from 3.5 km^2 in 2010/11 to 5.5 km^2 in 2011/12. Considering this development, it is likely that investments in new power plants will be necessary in the near future. In addition, it is worth to point out the room for improvement in the villages heating system, where the coal is burned in inefficient stoves, with consequent high pollution inside the houses and health risks for the inhabitants. Reed can thus represent a possible source to satisfy (or contribute in satisfying, supplementing the traditional sources) the energy demand and at the same time reduce exposures by use of modern stoves.

According to the above-ground yield measured in each plot and the calorimetric analyses of the corresponding samples, the average energy content of reed is 242.4 GJ/ha. The average potential is therefore 181.8 GJ$_{th}$/ha in the case of heat production in biomass furnaces, 55.3 GJ$_{el}$/ha and 135.5 GJ$_{th}$/ha in the case of gasification based CHP plant and 59.2 GJ$_{el}$/ha and 152.3 GJ$_{th}$/ha in the case of CHP in a direct combustion system.

Focusing on the reed managed by the lake administration and considering the present harvested amount of 100,000



(a) **(b)**

Fig. 8 – CHP (a) electrical and (b) thermal gross efficiencies in function of the gasifier operating conditions, whit highlighted the values assumed for the scenario evaluation.

Table 6 – Potential thermal (and power) output and indicative number of flats that can be heated according to the considered scenarios.

	Present	Potential	
Harvested amount [t/ha]	5.3	14.1	
Scenario 1	276	925	GWh_{th}
(biomass furnaces)	8.53–9.60	28.55–32.12	thousands of flats
Scenario 2	84	281	GWh_{el}
(CHP gasification)	206	689	GWh_{th}
	6.36–7.15	21.28–23.94	thousands of flats
Scenario 3	90	301	GWh_{el}
(CHP combustion)	231	775	GWh_{th}
	7.14–8.04	23.91–26.90	thousands of flats

tonnes (corresponding to about 5.3 t/ha as average yield on the total reed covered area) and a material loss of 12% (value confirmed by lake administration officials), the present utilization of reed is equivalent to a total energy input of about 1327 TJ. Considering the measured dry matter yield of 14.1 t/ha, the total energy input could be potentially increased more than 3 times by harvesting the total available biomass (according to [81] only 4% of the total lake area is harvested at the moment).

In Table 6, the potential thermal (and power) output of the considered scenarios, at the present and potential conditions, is reported, the indicative number of flats that can be heated is calculated assuming a typical flat extension of 60 m^2 and a thermal demand of 80–90 kWh/(m^2 month).

It is worth to point out the ratio between the average lower heating value (as received basis) of coal (about 23 MJ/kg is the average value for Chinese coal [82]) and reed (15 MJ/kg, Table 5), it means that the reed amount required to compensate the heating value of coal is about 53% higher.

3.6. *Economic assessment of energy uses of reed*

In order to perform an economic evaluation of energetic reed use, the coal and reed consumer prices need to be taken into account. As presented in sections 3.3 and 3.4, the raw material price for reed and coal was 370 CNY/t and 340–410 CNY/t in 2011, respectively. For private consumer in rural areas the coal price amounted to 700–780 CNY/t. Comparable consumer prices for reed are missing.

3.6.1. *Assessment and comparison of the different scenarios*

Scenario 1 considers a decentralised use of reed in household stoves. For this application reed has to be pressed into briquettes or pellet. Taking into account the current costs for pressing (117 CNY/t), a consumer price for the reed briquettes (or pellets) of 490 CNY/t may be reasonably assumed [49]. In this calculation, transportation costs have been neglected due to the fact that the household consumers are assumed to be close to the wetland. Moreover, the current reed price already includes transportation to the lakeshore.

For Scenarios 2 and 3, considering the centralized CHP production (Scenario 2: gasification based conversion; Scenario 3: direct combustion), chopping of reed would be required, which costs 11 CNY/t according to [83]. Considering transportation cost of 50 CNY/t, the final reed price would be 431 CNY/t and the production costs will reach 0.029 CNY per MJ/kg.

Scenario 4 considers the direct co-firing of reed in existing coal plants in the near town Urad Qianqi, which efficiency is 85% according to the survey. Considering a decreasing of 1.65% of the efficiency of the plant with a reed share of 20% [18] and referring to the heated floor area of 5.5 km^2 in 2011/12, about 48,000 tonnes of reed would be required to provide the same amount of heat that is already provided to the district heating, with a decrease of about 27,000 tonnes per year of coal consumption. Considering additional costs for the transportation (50 CNY/t) and chopping (11 CNY/t) of the reed, a consumer price of 431 CNY/t is assumed. Under these conditions, the co-firing of reed would result in an increased production cost of 0.018 CNY per MJ/kg, which is slightly higher than pure coal firing (0.016 CNY per MJ/kg).

As can be seen from Table 7, the costs of pressed reed used in biomass furnaces (Scenario 1) and rural coal, normalized to the heating value, results in quite similar energy costs. The costs from reed gasification (Scenario 2) and combustion (Scenario 3) are significant higher than heating costs in coal plants. Costs for reed co-combustion (Scenario 4) result in only slightly smaller heating values and higher costs compared with pure coal plants. This results from the comparable small amount of 20% reed. Nonetheless, compared to the coal plant, the CHP plants fed with reed (Scenario 2 and 3) produces energy at two times the costs per MJ/kg. Scenario 4 shows only slightly higher costs compared to pure coal plants and might be competitive. However, the pure feedstock cost normalized by the heating value does not correspond necessarily to the final consumer price, which is also determined by other variables such as feedstock treatment and investment costs for the power plant.

3.6.2. *Economic feasibility*

Under current market conditions, the use of reed as an energy source looks promising for the combustion in reed stoves. Considering an efficiency of 40% for the coal stoves and the average utilization of 2.5 tonnes per year per and flat, the annual heat demand of a rural house can be estimated to about 6400 kWh. With the considered modern stoves, the same heat would be provided using about 2 tonnes of reed per year. Assuming a cost for the new biomass stoves of 1200 CNY [69], the payback period would be then less than 2 years. Also the co-combustion of reed (Scenario 4) in existing power plants looks economically feasible.

Scenario 2 and 3 will not be profitable under current conditions. This may change with increasing coal prices or if prices for CO_2-emissions will be implemented. A couple of renewable energy subsidies, such as guarantee for a connection to the grid, competitive tendering for renewable energy and a feed-in tariff for electricity from renewable energies, can be relevant for the present case study, in particular for the CHP scenarios (calculated below). Power plants with a biomass share smaller than 80% (Scenario 4) cannot be subsided under the current Chinese renewable energy law, which lead to co-firing only in demonstration cases [4,18]. A feed-in

Table 7 – Heating value and prices for reed and coal at Wuliangsuhai wetland.

	Present situation		Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Rural coal	Coal plant	Biomass furnaces	CHP gasification plant	CHP plant fed by reed	Co-combustion (20% reed, 80% coal)
LHV [MJ/kg]	23	23	15	15	15	21
Average purchasing price per kg(a) [CNY]	0.740	0.375	0.490	0.431	0.431	0.386
CNY per MJ/kg	0.032	0.016	0.033	0.029	0.029	0.018

[a] Inflation adjusted from February 2004 to February 2011 according the consumer price index in China reported in Ref. [84].

tariff, paid in China for electricity from renewable energies by the grid company to purchasers, has been considered. Theoretically, a gasification and combustion bio-energy plant of 10 MW or potentially 30 MW can be fed with the available reed resources, considering the presently exploited and the potentially available reed, respectively.

The net present value for the investment of the two solutions, are shown in Table 8. The net present value (NPV) is the present value of the annual net benefits minus the investment costs. The NPV of scenarios 2 and 3 were calculated considering a real interest rate of 3%, annual operational time of 7500 h and a plant lifetime of 20 years. Additionally a sensitive analysis haven been made with a real interest rate of 1.5% and 5%.

For the gasification-based CHP plant, operation and maintenance as well as investment costs have been estimated by comparison with the average values of biomass power plants in China in 2004 [85] (the values have been inflation adjusted from February 2004 to February 2011 according the consumer price index in China reported in Ref. [84]). More recent data have been not available. In order to take into account the economy of scale, the available values have been interpolated in function of the plant scale, obtaining an investment cost of 16.56 and 11.60 million of CNY per MW for the 10 MW and the 30 MW plant size, respectively, and an operation and maintenance cost of 5.45 and 2.18 million of CNY per MW for the 10 MW and the 30 MW plant size, respectively.

For the direct combustion based CHP plant, the investment cost have been estimated as an average of the costs presented in Refs. [83], resulting equal to 9.55 million of CNY per MJ. In this case, economy of scale has not been considered, since the available reference cases, referring to plant sizes in the range 4–30 MW, showed similar unit costs. From the same source, an operation and maintenance cost of 0.179 CNY/kWh (resulting equal to about 1.34 million of CNY per MW, considering 7500 h of operational time per year) has been derived. For reasons of simplicity, the reed price, taken from interviews in 2011, the income from selling electricity and the marginal costs for reed harvesting have been assumed to remain at the same real value in the next 20 years.

An electricity feed in tariff of 0.75 CNY/kWh is considered to be paid by the grid operator to the power plant for 15 years according the Renewable Energy Law [6]. After that period, the general energy price is assumed to be equal or higher than the feed in tariff due to increasing energy prices. Benefits from heat provision are not considered under this scenario.

Obviously, the 10 MW gasification CHP plant is not profitable because the annual reed and operation and maintenance costs alone exceed the annual revenues, leading to negative annual net benefits. The results for a 30 MW gasification CHP plant are slightly better, leading to a positive present value of the annual benefits, but including the investment cost to a negative NPV. These options are not economic feasible under current conditions. A sensitivity analysis has shown that also a interest rate of 1.5 or 5% will influence the NPV only slightly.

Table 8 – NPV and payback period for power from gasification and direct combustion CHP plants (2011).

Power plant setting	CHP gasification		CHP direct combustion	
Plant size	10 MW	30 MW	10 MW	30 MW
Annual electricity production (MWh)	75,000	225,000	75,000	225,000
Annual amount of reed (Thousand tonnes)	78.56	235.67	73.40	220.21
Annual costs (Million of CNY)				
Reed	33.86	101.57	31.64	94.91
Operation and maintenance	54.48	65.28	13.43	40.28
Annual benefits (Million of CNY)				
Selling electricity	56.25	168.75	56.25	168.75
Annual net benefits (Million of CNY)	−32.09	1.90	11.19	33.56
Present value of annual net benefits (Million of CNY)	−477.43	28.26	166.44	499.31
Total investment (Million of CNY)	165.63	347.89	95.52	286.55
NPV (Million of CNY)	−643.05	−319.63	70.92	212.76
Payback period (Years)	–	183.1	8.5	8.5

For reed combustion the results look more promising for both plant sizes. The NPV is around 71 Million CNY and around 212 million CNY for the 10 and 30 MW plant, respectively. A sensitive analysis with an interest rate of 1.5% and 5% has proven that the investment is still profitable for both power plants sizes. On the one hand, decreasing investment costs due to high rate of innovation in this field and increasing energy prices would positively influence the NPV of CHP. On the other hand, labour and transportation costs may rise due to the economic growth and rising energy prices. However, the results in general show the potential of wetland plants and that the energy utilization can be competitive to coal even under current conditions.

From the perspective of reducing greenhouse gas emissions, a local utilization should be favoured over long distant transportation. Benefits can possibly be increased by accounting the greenhouse gas emission mitigated by use of biomass energy under the Kyoto Protocol. Clean Development Mechanisms (CDM) in the United Nations Framework Convention on Climate Change are implemented to allow developing countries reducing their greenhouse gas emissions by financing mitigation project in developing countries. Each tonnes of CO_2-equivalent reduced can be traded as "Certified Emission Reduction" (CER) on the international carbon market [86]. Renewable energies projects play only a minor role in CDM project and mostly in large scale, due to the high transaction cost (e.g., only 27% of the emission reduction in CDM came from renewable energies in 2008 [86]). Unfortunately the price for CER experienced a rapid decline in recent years, accounting only for 0.32$/CER in November 2013 [87]. Only if the prices increase again CDM can play a role in financing reed CHP plant at Wuliangsuhai Lake. Considering that the CO_2 emission factor for coal is 0.093 kg/MJ [88], 86.7 and 260.0 thousands of tonnes of CO_2 could be saved in the gasification based CHP scenario for the 10 MW and 30 MW plant respectively. Because of the slightly higher considered efficiencies, for the case of direct combustion these values are slightly higher, 89.7 and 269.2 thousands of tonnes of CO_2 for the 10 MW and 30 MW plant respectively. In the distributed generation scenario 92.5 and 309.7 thousands of tonnes of CO_2 could be saved, assuming to fully exploit the presently and potentially harvested reed, respectively. Finally, considering that a tonne of coal would produce about 3 tonnes of CO_2 [88], in the co-combustion scenario about 81.7 thousands of tonnes of CO_2 can be saved.

Finally, non-market values could be considered in a holistic management scheme for the Wuliangsuhai Lake. Regular harvest of reed removes a considerable amount of biomass from the lake which prevents a rapid silting and "second pollution" by decomposing. Also for local job creation in the "death" winter time the reed cutting plays an important role employing up to 2000 worker at the moment. Reed energy use could be replace the current reed use for paper production which is increasingly under threat [49].

4. Conclusions

Reed is a plant with multiple functions and services. Many of them are overlooked up to now. Commercial utilization of reed can raise awareness regarding the importance of the wetland, but has to be analysed regarding profitability under market conditions. This paper evaluated the energetic use of reed in remote areas of North China under the scenarios of local decentralised heating, large-scale combustion and gasification CHP plants and reed co-combustion in existing coal plants.

The evaluation has shown that reed has the potential to act as an energy feedstock at Wuliangsuhai conditionally. As a renewable resource, it can be a sustainable alternative to highly health and environment damaging coal in the local and big scale in terms of income source, lake restoration and maintenance. For the use on household level, we conclude that it is highly competitive against coal. For CHP plants the situation is completely different but still the energy use of reed is profitable under certain assumptions, in particular the renewable energy subsidies. The same is true for co-combustion in existing coal power plants. In fact, it cannot be subsidized under current law, but through the use of exiting plants and the comparable low share of reed at the total feedstock it is still profitable. This way seems quite promising, as it is easy to implement, does not require high investments and still has a good profit. However, as it is still a bit more costly, it is questionable if someone would go this way without any incentives from government side. Not competitive would be reed gasification in a CHP plant under current conditions. The negative NPV value gives a clear hint that it requires more research and technologic innovation on that technology. Future business profitability of reed as an energy source will depend on several factors, mainly the coal price, subsidies for biomass energy, CO_2-avoidance costs and the reed price, which relies mainly on harvesting labour costs.

Apart from the economic analysis the positive impact of reed use for the lake maintenance and the ecology should be highlighted. Reed harvesting fulfils an important function for the removal of nutrients and water purification from the polluted lake. By this, it helps to maintain and restore the lake and its functions. To utilize the harvested for energy in a CHP plant can avoid 86 and 300 thousands of tonnes of CO_2, a circumstance which, together with the better air quality, for the China, which struggles with heavy air pollution, is tremendously important.

Up to now, the Chinese energy policy was focusing mainly on large-scale power industry, many of them in the developed south-east. Small, decentralised projects, which are important for the remote rural areas lack support. One reason is the shortfall of renewable energy law implementation, such as refusal of grid connection for power plants by big energy companies or technical problems to handle irregular geed from renewable resources. The dominance of state, coal based, energy business currently prevents the growing of alternative decentralised, mostly renewable energy based bottom-up approaches.

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